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EFFECT OF SONICATION TIME AND PARTICLE VOLUME FRACTION ON THERMAL CONDUCTIVITY OF ALUMINA NANOFLUIDS

INTERIM REPORT
TFLRF No. 453

by
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for
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Force Projection Technologies
Warren, Michigan

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EXECUTIVE SUMMARY

This research work was performed to gain further understanding into possible trends between thermal conductivity enhancement, particle volume fraction and the total number of aggregate clusters for different sonication times. The research objective was to use analytical modeling to determine the thermal conductivity enhancement of nanofluid samples, with overall particle volume fraction from 1% to 5%, at two different power levels, 70 W and 100 W. The nanofluids were subjected to different sonication times such that the overall energy that was imparted to the nanofluid per unit volume remained the same. The first conclusion was, the highest thermal conductivity enhancement and the maximum number of nanoparticle clusters, occurred at different volume fraction and sonication time, for at both power levels.

The second important conclusion was, at both power levels, 4% volume fraction yielded nanofluids with highest thermal conductivity enhancement. For thermal conductivity enhancement from 16% to 35%, the maximum cluster size was on the order of 200 nm, while, for thermal conductivity enhancements from 135% to 173%, the maximum cluster size was restricted to 500 nm. It should also be noted that highest thermal conductivity enhancements in excess of 100% of the base fluid were achieved only if sufficient number of nanoparticles were present in the base fluid and the current study concludes that such an optimum overall particle volume fraction was 4%.

FOREWORD/ACKNOWLEDGMENTS

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The author would like to acknowledge the contribution of the TFLRF technical support and the TFLRF Administrative staff.

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ACRONYMS AND ABBREVIATIONS

%	Percent
KJ	Kilo Joule
min	minute
mL	milliliter
nm	nanometer
SEM	Scanning Electron Microscope
SwRI	Southwest Research Institute
TARDEC	Tank Automotive Research, Development and Engineering Center
TFLRF	U.S. Army TARDEC Fuels and Lubricants Research Facility
UTSA	University of Texas at San Antonio
W	Watts

1.0 INTRODUCTION, OBJECTIVE AND PROJECT SCOPE

The research study that was published in TFLRF Report No. 443 titled “Scanning Electron Microscope (SEM) Studies on Aggregation Characteristics of Alumina Nanofluids” investigated the size of nanoparticle aggregates as a function of sonication time and number of particles that were present in each aggregate. [1] The overall conclusion was that increase in sonication time did not have a significant change on cluster growth and number of particles per aggregate, when the overall volume fraction of alumina nanoparticles was constant. The objective of this research was to use analytical model developed by Wang *et al*. [2] to determine the thermal conductivity of the nanofluid samples that were subjected to different sonication times, at different overall particle volume fractions, and two different power levels. Task 2.3 in WD20 was funded to accomplish this research objective. Under this task, no new experimental design or model were developed. Rather, the goal of this research was to gain further understanding into possible trends between thermal conductivity enhancement, particle volume fraction and the total number of aggregate clusters for different sonication times.

2.0 TECHNICAL BACKGROUND AND THEORY

The thermal conductivity of nanofluids that were reported in the comprehensive literature review by Özerinç *et al.* [3], were measured using instruments that operated the principle of modified transient plane source or transient hot wire method. The modified transient plane source operates by applying a small amount of heat to a fixed static sample volume through a spiral heating element. The temperature rise at the interface of the sample and the heat source induces a change in the voltage drop of the sensor element. The voltage rise is steeper for more insulative materials and vice versa. The instruments based on modified transient plane source are calibrated using homogeneous liquids and homogeneous powders to calculate thermal conductivity of unknown samples. However, these calibration values are not applicable to a non-homogeneous fluids containing a mixture of liquid and nanometer size particle clusters of varying sizes. Thus, the lack of calibration models and values for non-homogeneous fluids, in a transient plane source instrument, makes it inadequate for measuring thermal conductivities of nanofluids.

The second type of instrument widely used for thermal conductivity measurements is the transient hot-wire technique. The wire immersed in the sample is electrically heated and the change in resistance of the wire and hence, the temperature, is measured as a function of time using Wheatstone bridge. The thermal conductivity value is determined from heating power and slope of temperature change as a logarithmic function of time.

The disadvantage of the transient hot wire method is possible current flow through the liquid containing metal nanoparticles causing ambiguities in measurement of heat generated in the wire resulting in distortion of output voltage signal due to conducting liquid in the cell and polarization of the wire surface was reported by Kostic and Simham [4]. The nanoparticles also adhere to the surface of the wire causing fouling issues and biased thermal conductivity measurement. In addition to the above disadvantages, the tension in the wire changes with applied heat causing strain, which affects the electrical resistivity of the wire contributing to errors in measured thermal conductivity values. Due to these reasons, the current work focuses on determining maximum enhancement in thermal conductivity values through analytical modeling.

The analytical model that was developed by Wang *et al*. [2] was not simply based on the overall volume fraction of nanoparticles present in the fluid. Rather, it integrates the thermal conductivity of clusters of particles and the total number of such clusters over the entire size range to obtain the overall thermal conductivity of the nanofluid. The mathematical formulation for calculating thermal conductivity of nanofluids containing cluster of nanoparticles aggregates, was discussed in detail in TFLRF Report No. 443. [1] The test matrix and results from this report was used for computing thermal conductivity of clusters using Wang model. The following section describes the results in terms of the total number of clusters and overall thermal conductivity of the nanofluid over different total particle volume fractions versus sonication time.

3.0 RESULTS: ANALYSIS AND INFERENCE

The results obtained were computed thermal conductivity values and total number of nanoparticles clusters for nanofluids with total particle volume fraction from 1% to 5% and sonication time from 20 minutes to 80 minutes, at 70 W; and 14 minutes to 56 minutes at 100 W. The total energy density imparted to the nanofluid, at both power levels, varied between 3.33 KJ/mL to 12.77 KJ/mL for the respective sonication times. Figure 1 shows the ratio of thermal conductivity of the nanofluid to the thermal conductivity of the base fluid at 70 W. The maximum enhancement in thermal conductivity was estimated for a nanofluid with a total particle volume fraction of 4% for 50 minutes sonication, at 70 W. The energy imparted to the nanofluid at this power level and sonication time was 8.148 KJ/mL and the total number of nanoparticle clusters were 4.49×10^8.

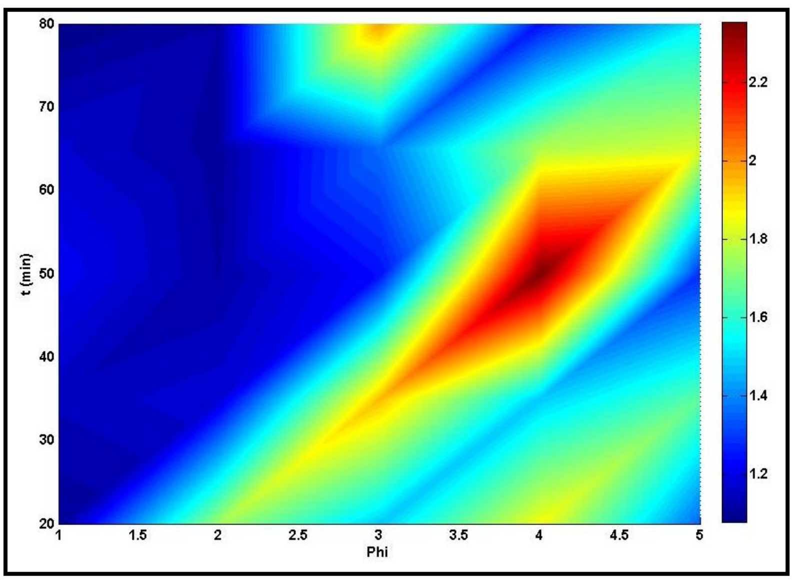

Figure 1. Ratio of Thermal Conductivity of Nanofluid to base fluid at 70 W

Figure 2 shows the total number of nanoparticle clusters over the entire volume fraction sonication time test matrix. The highest thermal conductivity enhancement that occurred at 4% volume fraction and 50 minutes sonication time, at 70 W, did not imply that the total number of nanoparticle clusters were a maximum at that volume fraction and sonication time. Rather, the

maximum number of nanoparticle clusters, at 70 W, occurred at 1% volume fraction for a sonication time of around 65 minutes with 1.83×10^9 nanoparticle clusters, with the thermal conductivity enhancement being a relatively lower value.

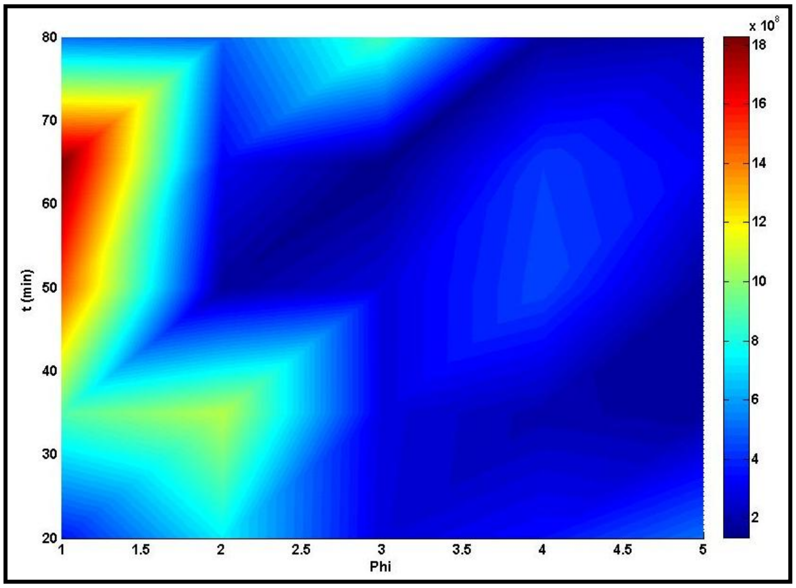

Figure 2. Total Number of Nanoparticle Clusters at 70 W

Figure 3 compares the distribution of the total number of particles as a function of nanoparticle cluster diameter between points that have maximum thermal conductivity and maximum total number of points. While, the total number of particles was a maximum for 1% volume fraction at 65 minutes, the nanoparticle cluster diameter is restricted to 200 nm, resulting in a thermal conductivity enhancement of 16.3%.

For 4% volume fraction at 50 minutes sonication, most of the particles were under 400 nm, except for a fraction of clusters that have a diameter of 1011 nm. This micro-sized particle was responsible for thermal conductivity enhancement of 135.41%. Based on the results in TFLRF Report No. 420 [5], it was concluded that larger micro-sized clusters are unstable and break down into smaller nanoparticle aggregates.

Upon excluding the contribution of such micron sized particle to thermal conductivity enhancement in Wang model, the overall thermal conductivity enhancement reduced to 26.7% at

4% volume fraction for 50 minutes of sonication. In examining the particle size distribution further, nanoparticle clusters between 200 nm and 400 nm, gave a 10% thermal conductivity enhancement compared to 1% volume fraction nanofluid.

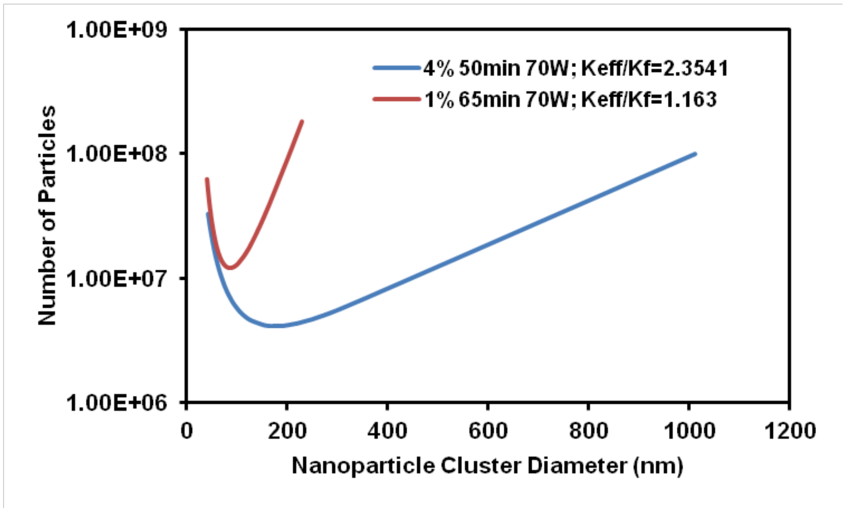

Figure 3. Comparison of Particle Size Distribution at 70 W

Figure 4 shows the ratio of effective thermal conductivity of the nanofluid to the thermal conductivity of the base fluid at 100 W power level. Figure 5 shows the total number of nanoparticle clusters over several volume fractions and sonication times at the same power level. In comparing the two figures, it can be inferred that 4% volume fraction provided the best thermal conductivity enhancement for all sonication time values compared to the rest of the volume fraction values at 100 W. However, the maximum total number of nanoparticle clusters were a maximum at 3% volume fraction for 25 minutes sonication.

Figure 6 shows the comparison between the two volume fractions and sonication times at 100W. It can be inferred that nanoparticle clusters were limited to a diameter of 500 nm. The total number of particles for 4% volume fraction and 56 minutes sonication was 1.87×10^9, while 3% volume fraction and 25 minutes sonication was 2.28×10^9. Similar to Figure 3, a broader nanoparticle cluster distribution for 4% volume fraction and 56 minutes sonication time provided a high thermal conductivity enhancement. While the net energy imparted to the nanofluid was

the same at both power levels, it can be concluded that 100 W sonication provides better thermal conductivity enhancement than 70 W sonication power level.

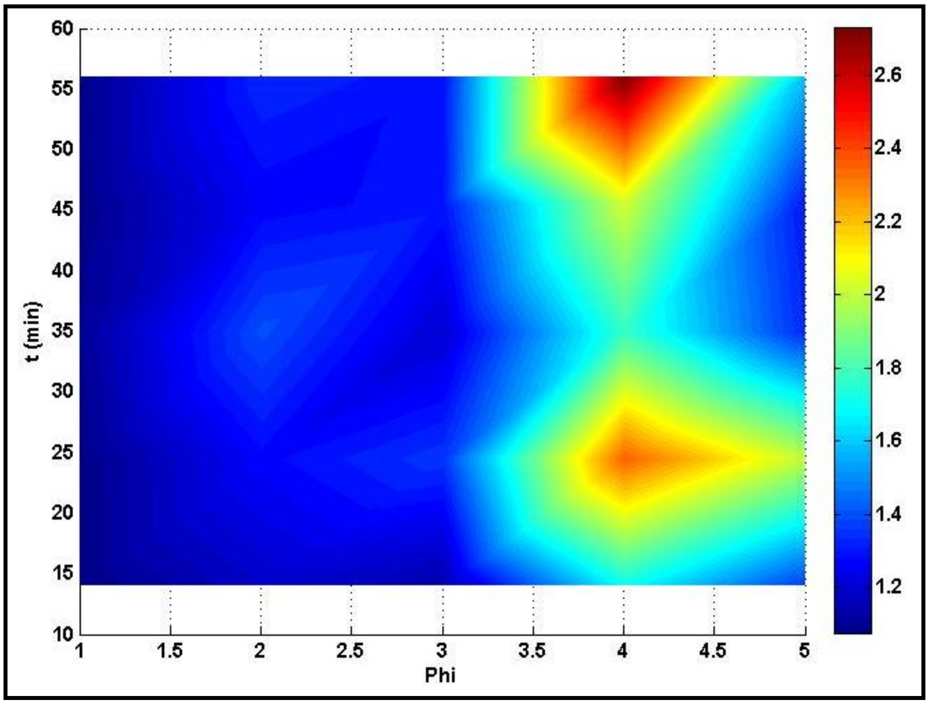

Figure 4. Ratio of Thermal Conductivity of Nanofluid to base fluid at 100 W

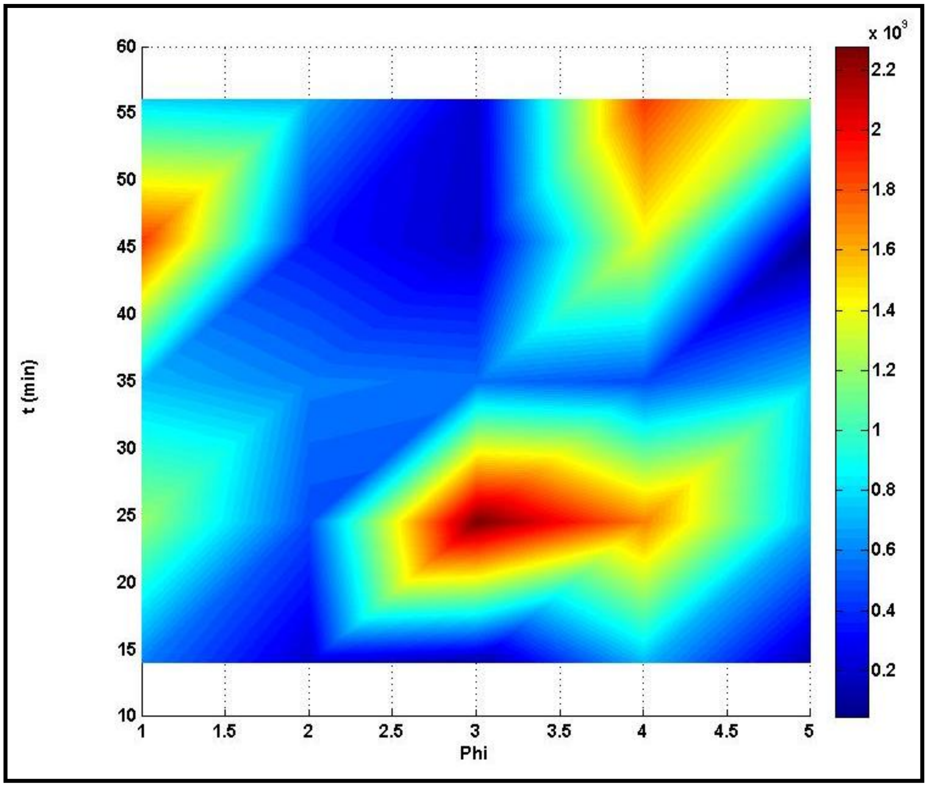

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Figure 5. Total Number of Nanoparticle Clusters at 100 W

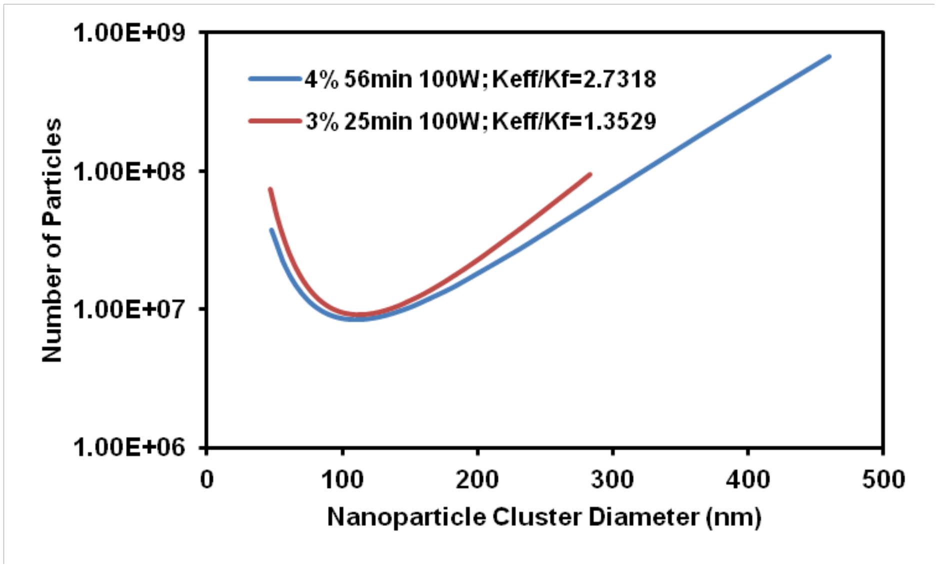

Figure 6. Comparison of Particle Size Distribution at 100 W

4.0 CONCLUSIONS

Two sets of nanofluids with overall particle volume fraction between 1% to 5% were sonicated at two different power levels, namely, 70 W and 100 W. At these power levels, the sonication time period was such that the total energy imparted to the nanofluid per unit volume remained the same. At both power levels, it was concluded that there is no direct correlation between volume fraction and sonication time parameters at which highest thermal conductivity enhancement was evaluated versus volume fraction and sonication time parameters at which maximum number of nanoparticle clusters were observed.

The most important conclusion is that, at both power levels, 4% volume fraction with 50 min to 56 min of sonication time yielded nanofluids with highest thermal conductivity enhancement. At this volume fraction, the particle size distribution was from 400 nm to 1000 nm. Since, larger aggregates lead to particle settling and are unstable, breaking to form smaller percolating

clusters, it can be concluded that stable nanofluids with high thermal conductivity enhancements should have cluster size restricted to 500 nm.

For thermal conductivity enhancement from 16% to 35%, the maximum cluster size should be on the order of 200 nm, while for enhancement from 135% to 173%, the maximum cluster size should be restricted to 500 nm. It should also be noted that highest enhancements in excess of 100% can be achieved only if sufficient number of nanoparticles are present in the base fluid and the current study concludes that such optimum overall particle volume fraction is 4%.

5.0 REFERENCES

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